First experience with plasma facing flowing liquid lithium (in EAST)*

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Liquid metal PFC seminar series
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Contents

1 Objectives of the ${}^{24}_{7}$FLiLi project

The present approach to fusion has exhausted itself at the level of TFTR, JET. It has no realistic path to the burning plasma.

During the first visit of ASIPP in 2008 I advised the Director of ASIPP J.Li

1. ***to develop and install the NBI as the highest priority for EAST as the long pulse device***
2. ***to develop the flowing lithium technology as another highest priority as key to new plasma confinement regimes (LIWF) relevant to 1000 s long discharges.***
3. ***the needs for thin Li layer flow was explained together with the importance of wetting.***

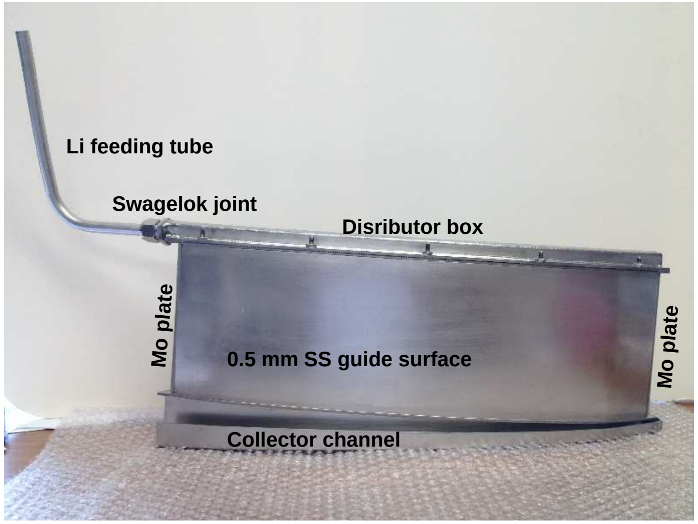
In 2009, the conceptual parameters and phenomenal burning plasma regimes of a the Fusion-Fission Research Facility (FFRF), essntially a DEMO of magnetic fusion, were presented to ASIPP.

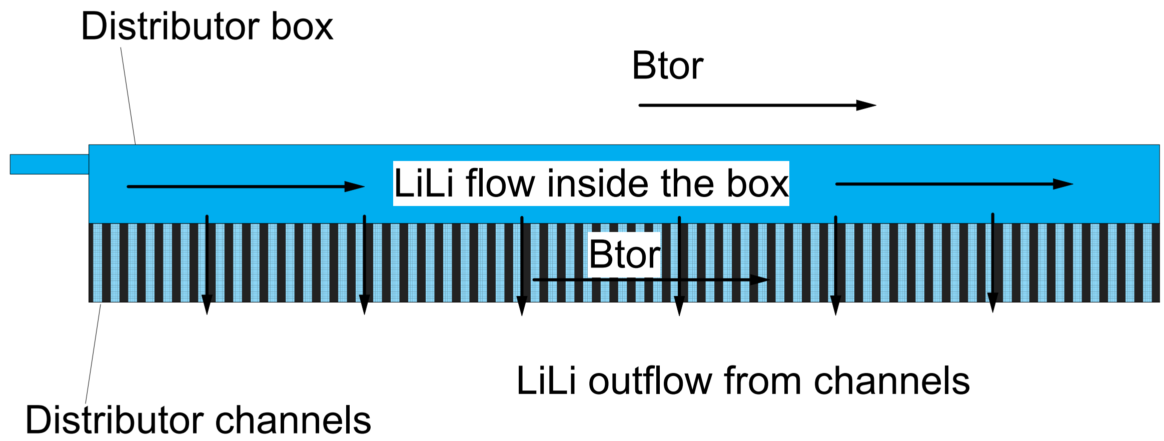
FFRF, utilizing the LiWF regime, with $P_{DT} \simeq 100$ ***MW and*** $Q_{electric} > 1$ ***and*** $I_{pl} = 5$ ***MA,*** $B_{tor} = 6$ ***T,*** $R/b/a = 4/1.6/1$ ***m/m/m based on existing technologies is in sharp contrast to the science-fiction giant DEMOs of FES.***

${}^{24}_{7}$FLiLiis the technology tool of LiWall Fusion concept

The idea behind the scene was the use of EAST demonstration of the LiWF regime for convincing JET to perform its future DT experiment in this regime and demonstrate $Q_{DT} > 5$.

Distributor for gravity driven thin viscous flow of LiLi was invented.



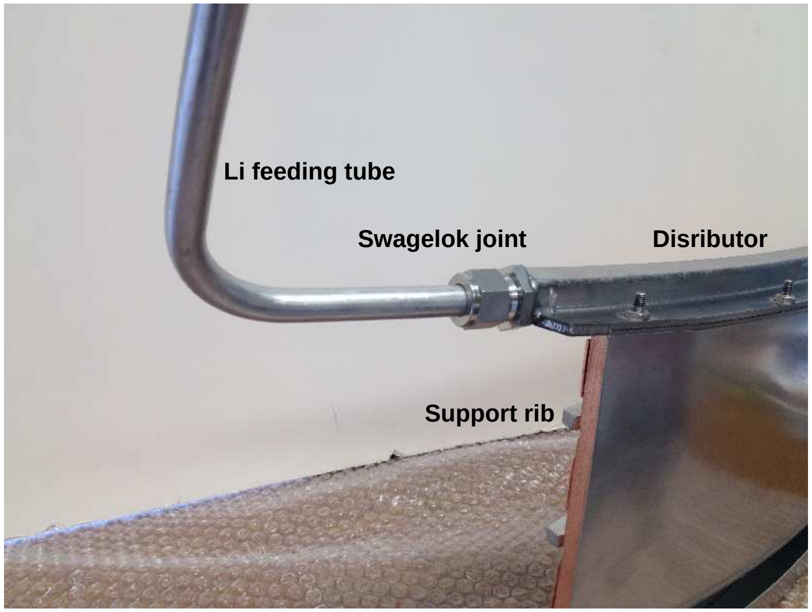


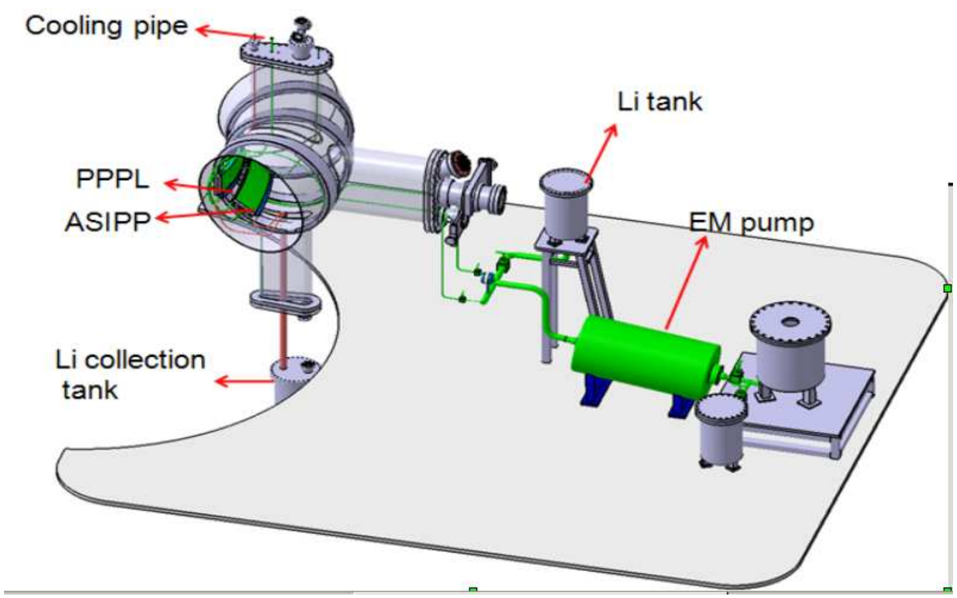
The key design idea, Chang-Lundgren formula

$$\Delta p_{\parallel}^{box} < p^{box} = \Delta p_{\perp}^{channels}, \quad \Delta p \simeq \sigma_E L \bar{V} B^2 \frac{\frac{\sigma_E^{SS}}{\sigma_E} d + 2\delta}{h + \frac{\sigma_E^{SS}}{\sigma_E} d}, \quad \delta \simeq \frac{1.3 \cdot 10^{-2}}{B_T} \textit{ [mm]}, \quad (2.1)$$

where L, h are the length and the size of the flow, d is the thickness of SS walls, δ is the Hartmann layer thickness.

Li feeding pipe and collector





Pressure drop $\Delta p^{FeedPipe}$ along the feeding pipe with inner radius a

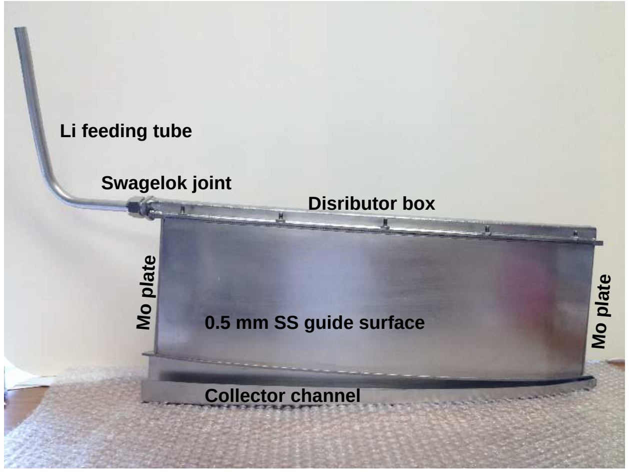
$$\Delta p_{Pa}^{FeedPipe} \simeq \sigma_E \bar{V}^{feed} \frac{\sigma_E^{SS}}{\sigma_E} \frac{d^w}{a} \int_{L^{feed}} (\mathrm{B} \cdot \mathrm{e}_l)^2 dl \simeq 16000 \cdot \bar{V}^{feed} \frac{d^w}{a} \left\langle L_m^{feed} B_\phi^2 \right\rangle . \qquad (2.2)$$

Because of MHD effect, the small flow rate of FLiLi can be controlled by the pressure in the Li tank at the level of a fraction of atmosphere

Drain velocity

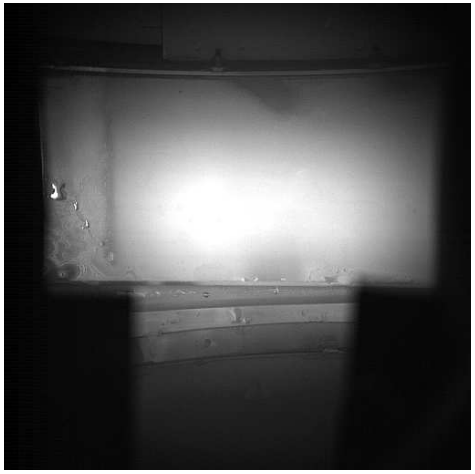
$$\rho g L^{drain} \simeq 16000 \cdot \bar{V}_{cm/s}^{drain} \frac{d^w}{a} \left\langle L^{drain} B_{\phi,T}^2 \right\rangle , \quad \bar{V}_{sm/s}^{drain} = \frac{5}{16} \cdot \frac{a}{d^w} \frac{L^{drain}}{\left\langle L^{drain} B_{\phi,T}^2 \right\rangle} . \qquad (2.3)$$

3 October 4, 2012: operational test in HT-7



PPPL July 29, 2012

HT-7 ASIPP, August 19, 2012



$P_{Ar} = 15$ kPa

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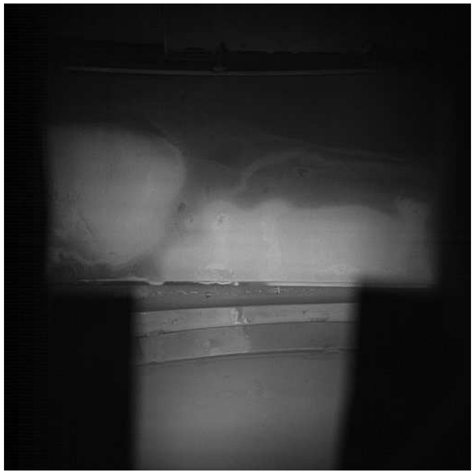
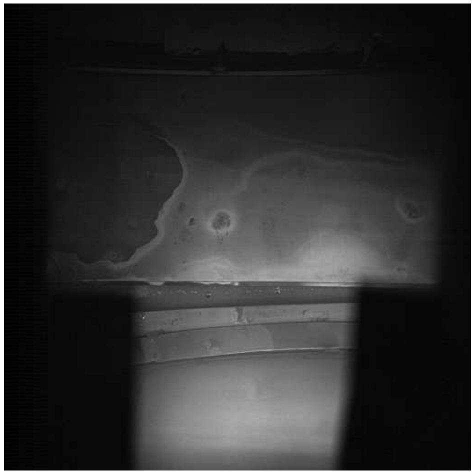


$P_{Ar} = 25$ kPa



$P_{Ar} = 40$ kPa

The in-vessel part of FLiLi system (a limiter) passed a successful test in HT-7 at $B_{tor} = 1.7$ T with and without plasma

4 Continuous ${}^{24}_{7}$FLiLi systems

${}^{24}_{7}$FLiLi addresses the most fundamental tecnology problem in utilization of LiLi in tokamaks, i.e., the high chemical activity of liquid lithium

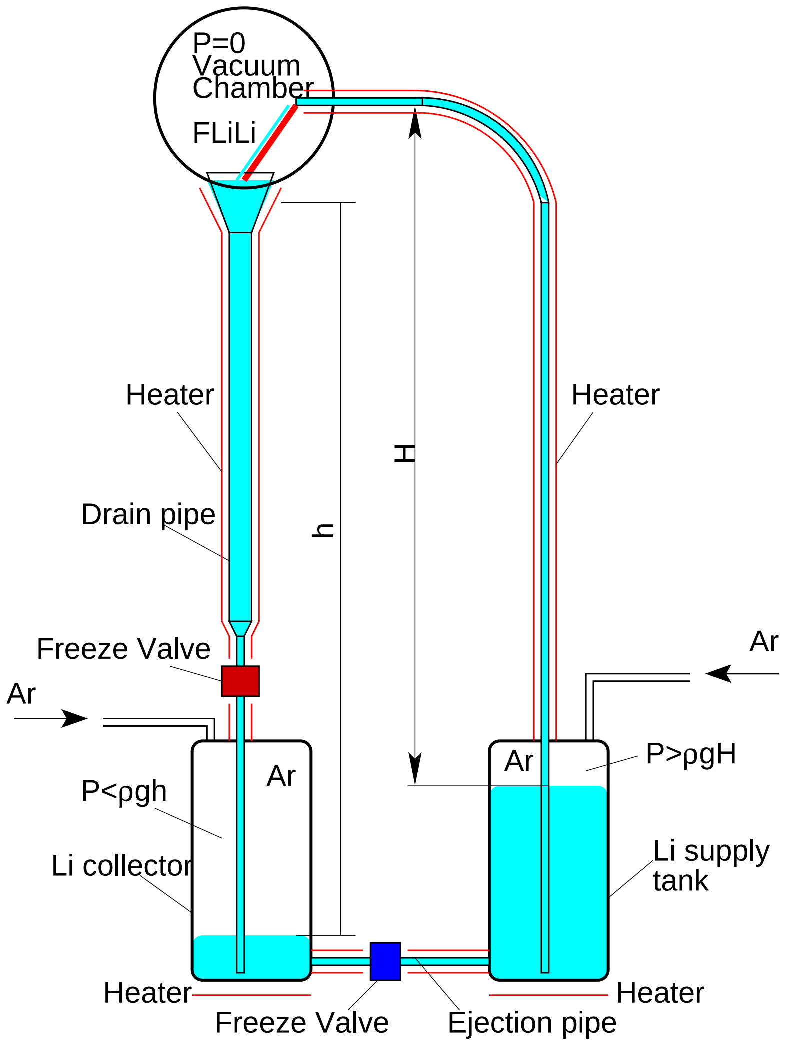
In fact, ${}^{24}_{7}$FLiLi utilizes the chemical activity of LiLi for improvement of in-vessel conditions.

FLiLi should work continuously:

24 hours per day, 7 days per week

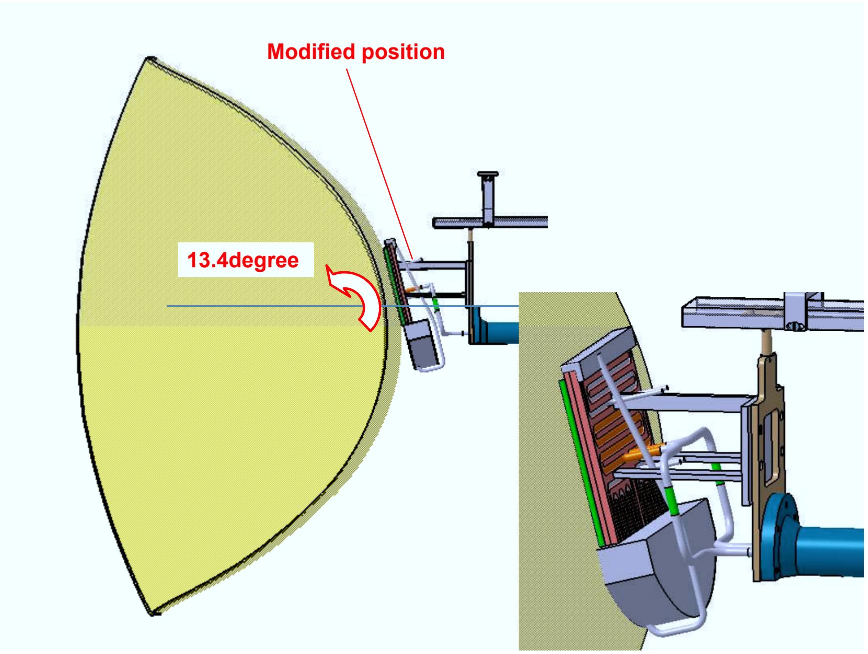
4.1 $^{24}_{7}$FLiLi controlled by Ar pressure

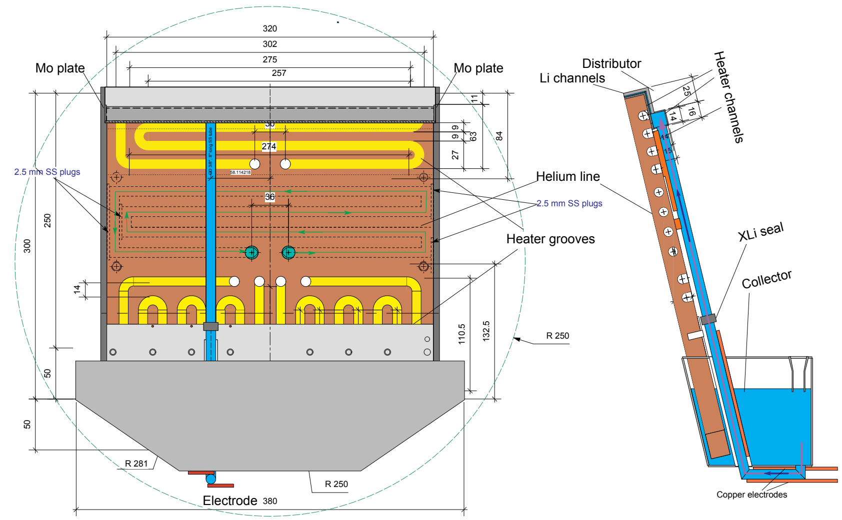
No mechanical moving parts in contact with LiLi. Ar pressure $\simeq$ 10s kPa.



The design concept and a partial implementation

5 $^{24}_{7}$FLiLi driven by JxB for EAST



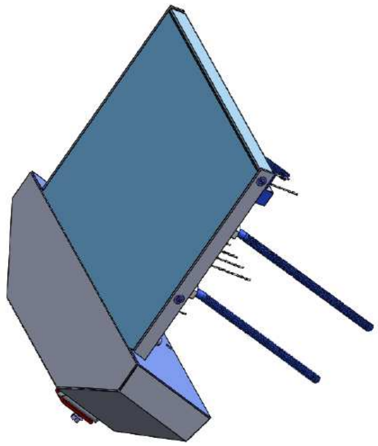


Copper coupon and collector

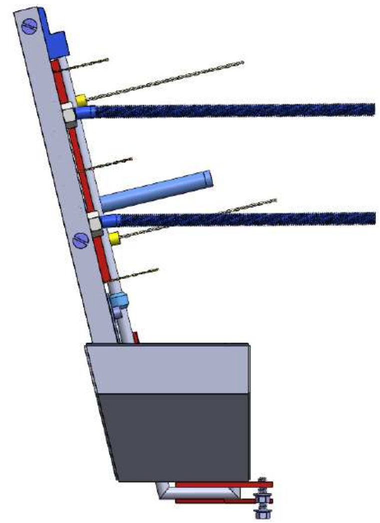
$^{24}_{7}$FLiLi Limiter inside EAST

5.1 Dimensions.

Copper coupon: 12.5” x 0.75” x 14.3”. Collector: 15” x 5” x 4.25”. Tilt 13.5^o.

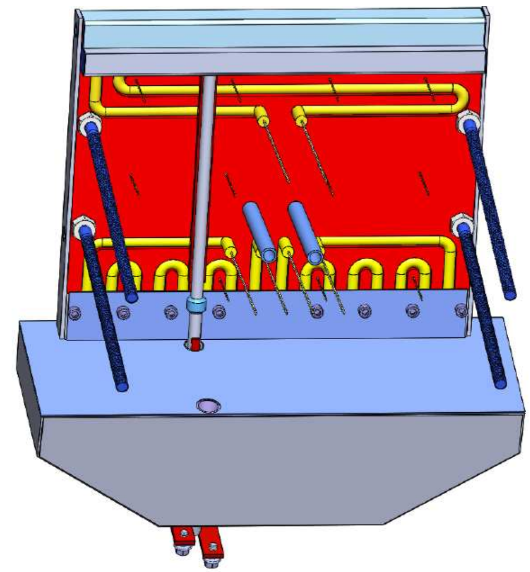


3-D Front view

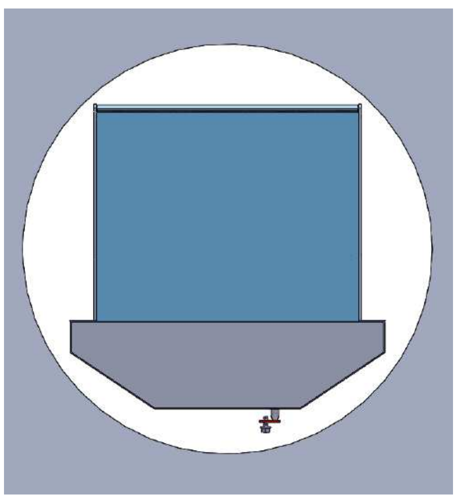


3-D Side view

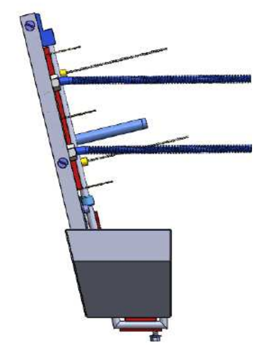
q



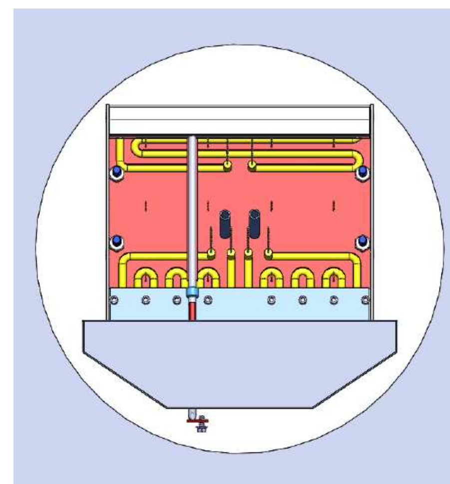
3-D Back view



Front view from the valve hole

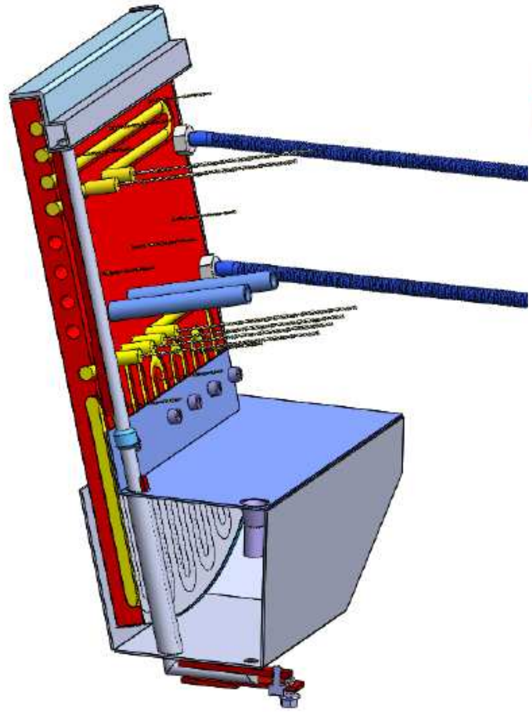


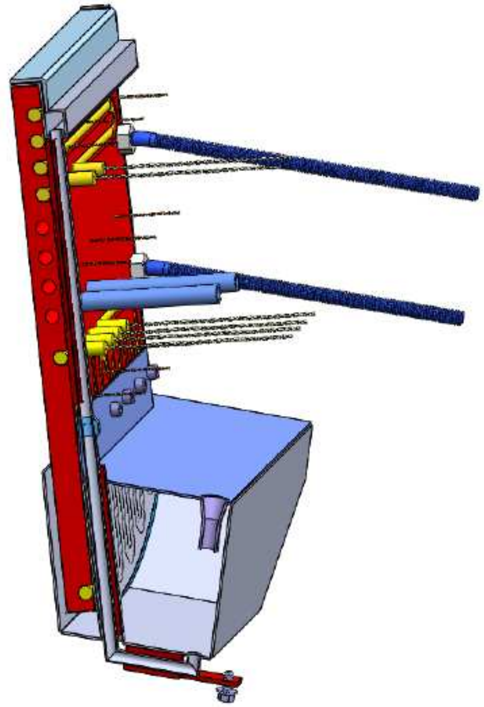
Side view

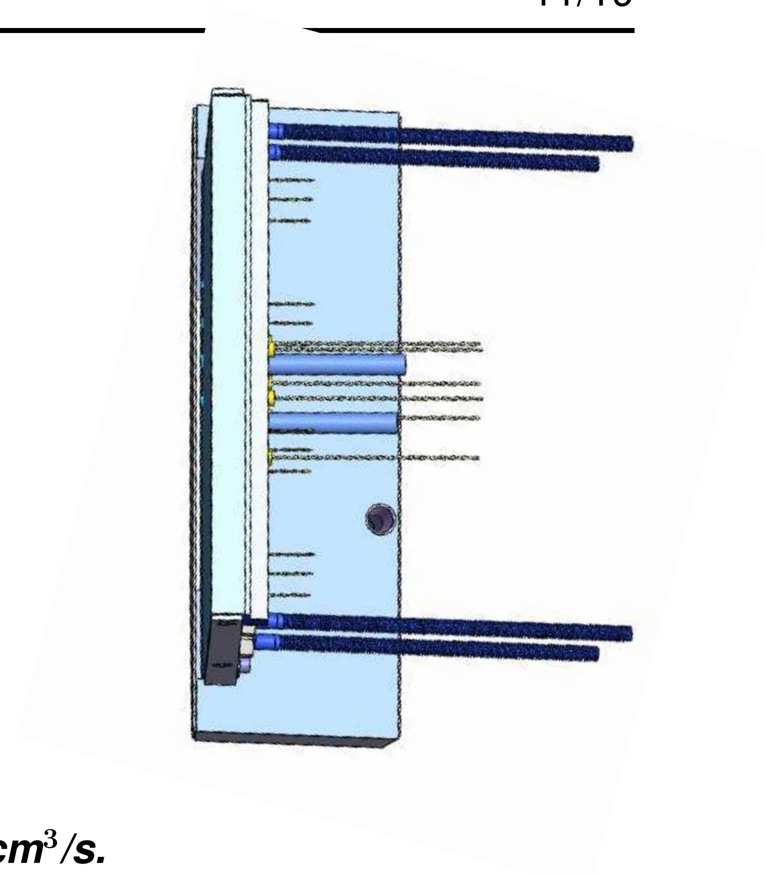


Back view toward the valve hole

5.2 Design







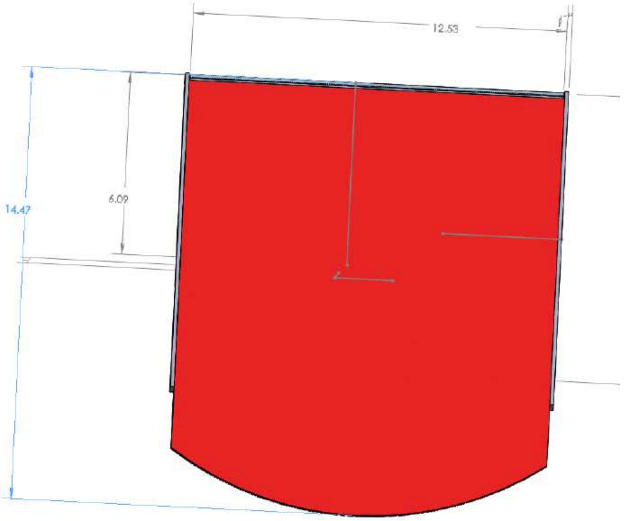
Tubing: 3/8", 0.020" walls. Flow rate of LiLi: $\Gamma = 1 - 2$ ***cm***^{3}***/s.***

Channel,	*LiLi Velocity, cm/s*	*Pressure drop, kPa*	
Distributor:	$0.8 \cdot \Gamma$	$0.5 \cdot \Gamma \cdot B_T^2$	*200 0.8x0.8 mm*^{2} *channels*
Feed tube:	$1.4 \cdot \Gamma$	$1.1 \cdot \Gamma \cdot B_T^2$	*18" long 3/8" tubing, 0.020" thick walls*
Height:		*1.85*	*weight of the LiLi column*
j x B drive:		$0.1 \cdot I_A^{EMD} \cdot B_T$	*Electromagnetic drive*

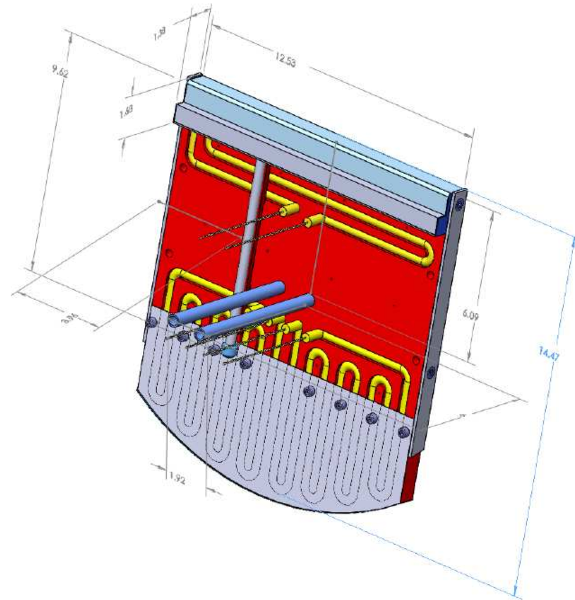
Voltage U ***in the high current line:*** $U_V = \frac{I_A^{EMD}}{125}\frac{L}{10}\frac{50}{S_{mm^2}}$

5.3 Copper heat sink

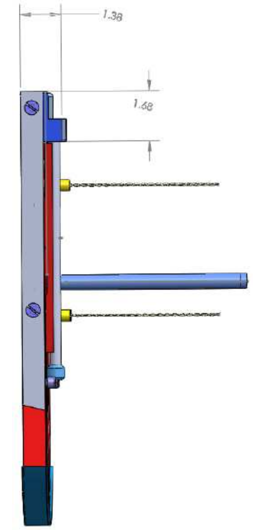
Copper heat sink, packaging drawings



Front view (SS foil not shown)



Back view



Side view

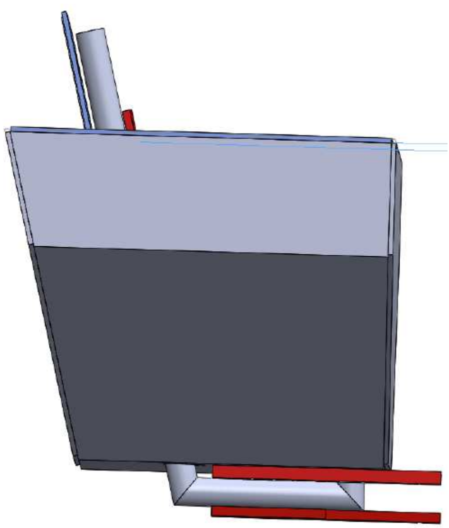
Each coupon contain

1. ***3 heaters (2 kW each, 220 V, 1 mm FeCrAl wire) with double wire ends***
2. ***Two 60 mm long pipes (OD/ID=12.7/9.5 mm) for interfacing with the 5 MPa He cooling system***
3. ***12 (OD=2mm, 12.7 mm deep) holes for thermo-couples***
4. ***4 3/8"-16 threaded rods for mounting***

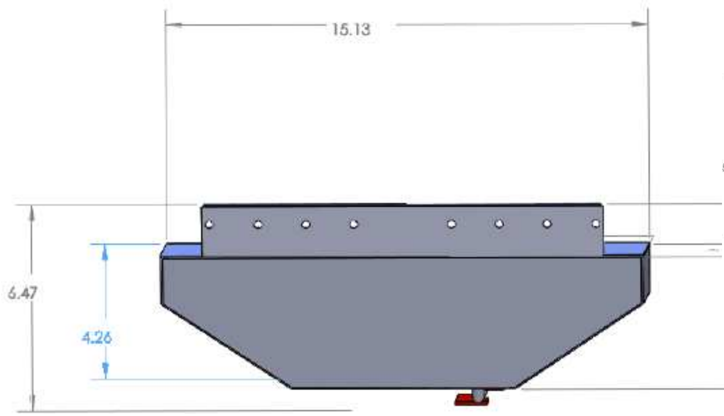
Heat capacity Q_{350^oC}= 2.56 MJ, Q_{200^oC}=1.46 MJ. Heating time 450 s and 300 s correspondingly.

5.4 Collector

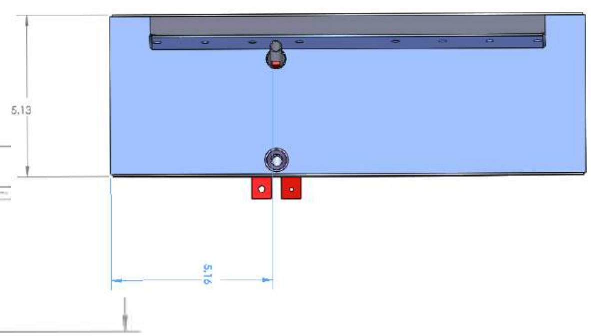
1. ***Collector is a separate part of the limiter***
2. ***Collector is a welded box (0.060" SS 316, Vol_{empty} =3.7 L, Vol_{net} =3.2 L) with***
   (a) ***a rectangular gap for the copper coupon at the top***
   (b) ***a hole for fueling at the top***
   (c) ***a Li feeding tube starting from the bottom***
   (d) ***two electric contacts for 200 A (voltage drop 0.001 V)***



Side view



Front view



Top view

1.5 L of LiLi heat capacity $Q^{LiLi}_{350^oC}$= 1.15 MJ, $Q^{LiLi}_{200^oC}$=0.66 MJ. Heating time with coupon 600 s and 420 s correspondingly.

5.5 Challenges in manufacturing the limiter

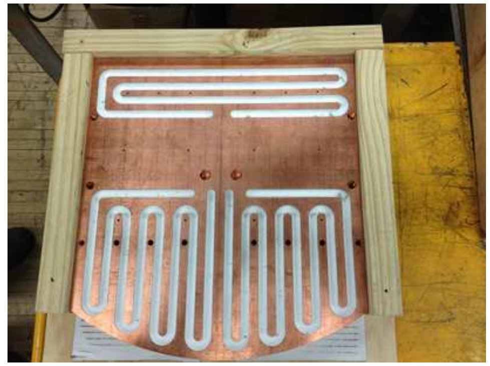
The 0.004" thick SS foil at the front surface of the coupon is an interface layer between LiLi and the copper body.

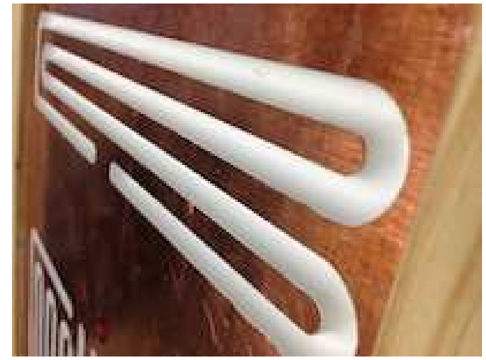
Welding 0.004" SS foil to the side 0.015" thick SS shim for protection of copper from contact with LiLi is one of manufacturing challenges

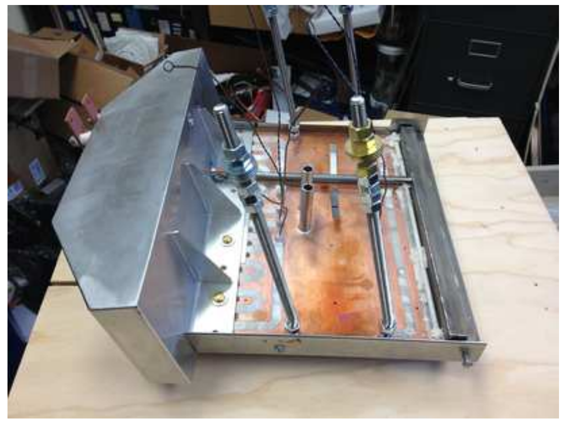
Another challenge is to braze the 0.004" SS foil to the copper body

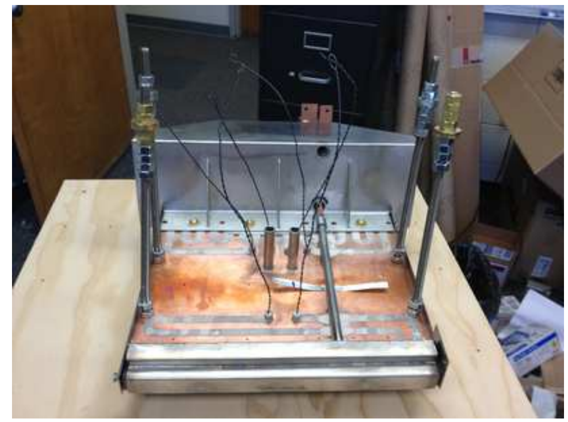
The brazing technology has its limitations. For future, it should be complemented by other approaches, e.g., HIP technology used in China for manufacturing the W-divertor.

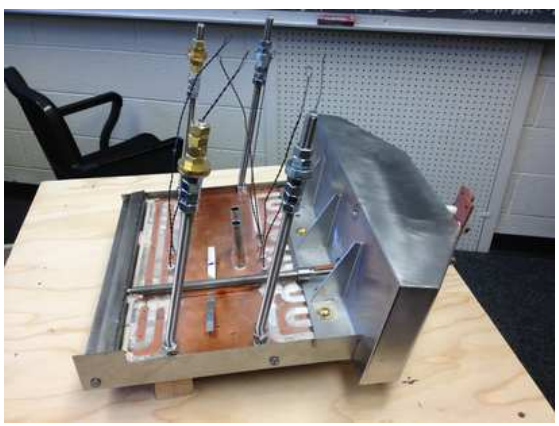
5.6 A fabricated limiter

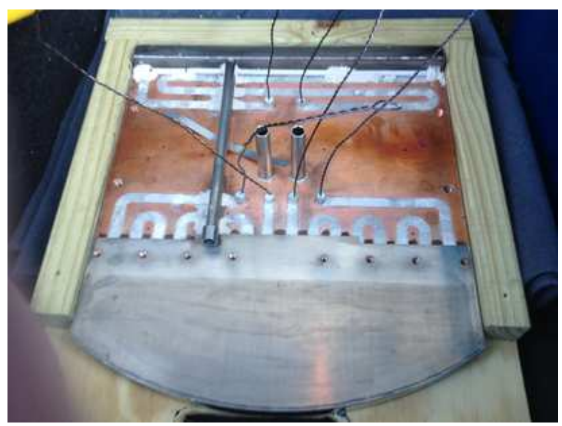






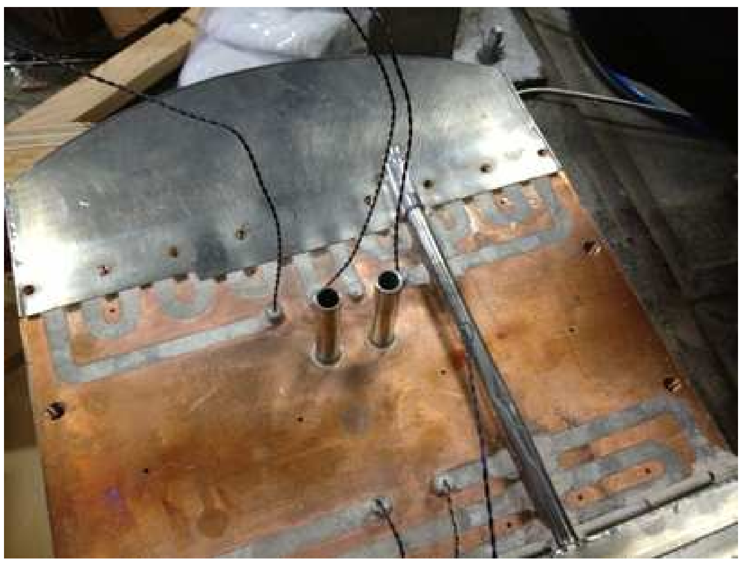


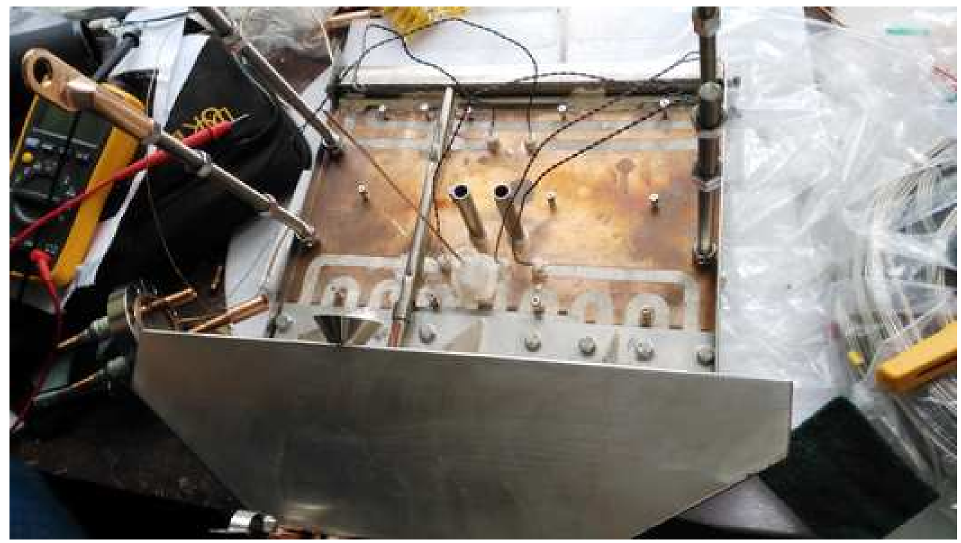




$^{24}_{7}$FLiLi limitrer for EAST

5.7 A delivered limiter

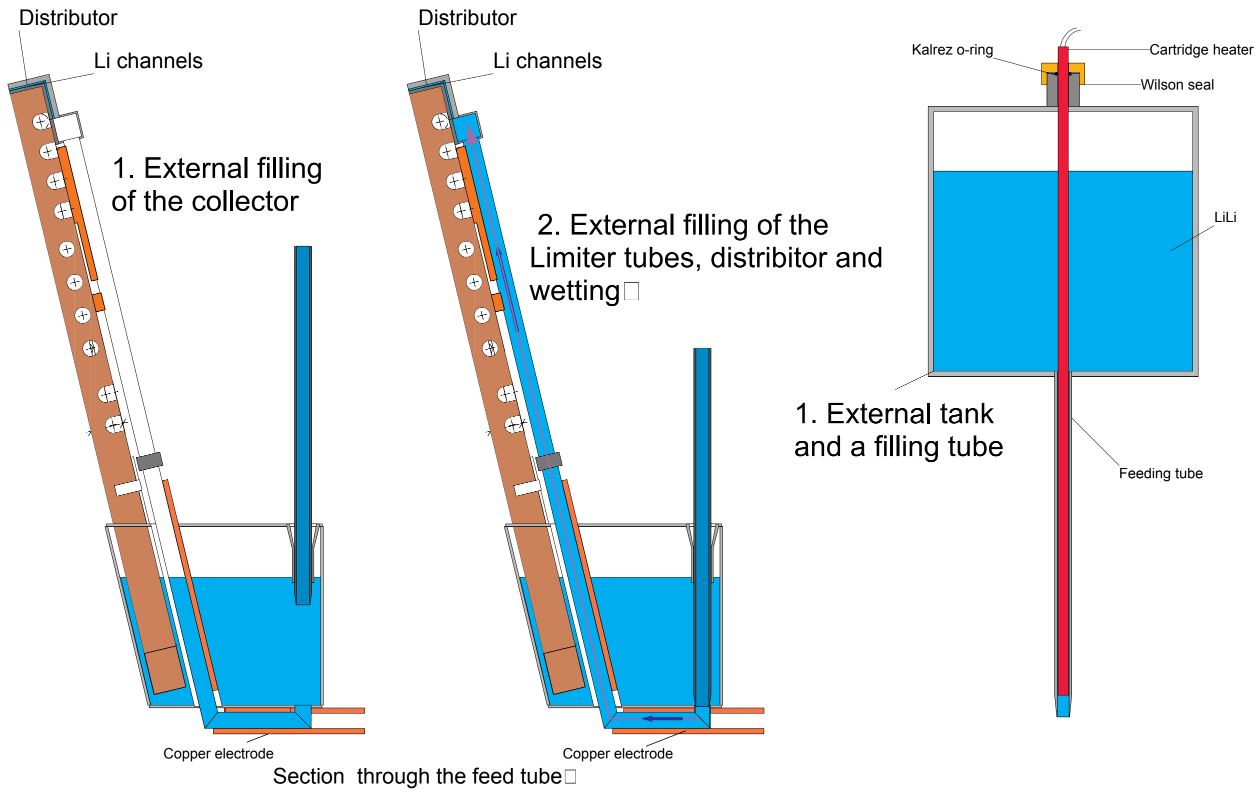




On heater terminal was broken during the custom inspection in Shanghai, repaired by ASIPP, but failed in the machine.

6 Initial filling, wetting, operation

3-D design model of the limiter, consistent with 3-D ASIPP EAST H-port model, was created.



1. ***Filling of collector with LiLi inside the exchange box using external Li tank***
2. ***Filing the distributor box and channels with LiLi***
3. ***Wetting the front surface inside the vacuum vessel (at working position of $^{24}_{7}$FLiLi)***
4. ***Continuous operation using electro-magnetic drive***

6.1 Post experiment pictures

Plasma heat flux evaporated SS foil covering the residual voids in brazing

The evident success:

1. ***3 hours of uninterrupted lithium flow was demonstrated, thus, making a breakthrough in the use of Li in tokamaks.***
2. ***The design of FLiLi elements: heaters, feed pipes, collector, electro-magnetic drive, distributor was robust and worked despite other failures.***

The lessons from failures

1. ***The thermal contact of collector with the copper was bad. Overheating of the copper caused most of the problem with the experiment.***
2. ***The SS surfaces were not cleaned properly. The thin layer flow was not achieved.***
3. ***The electric contact with the feed tube electrodes was incorrect: copper instead of SS.***

The first experience did not reveal any obstacle for developing reliable, compact, safe and practical $\frac{24}{7}$ FLiLisystems for tokamaks. The test was the first step enabling the development of 1000 s EAST plasma and of fusion relevant tokamak regimes.

The evident mistakes in the design are correctable. Brazing should be replaced by another technology. ASIPP should learn how to wet the guide surface.

16 years long DoE/PPPL ignorance of LiWF has to be terminated. LiWF is not LDRD.
LiWF is the only realistic way to burning plasma. goal.
A dedicated DoE project should be initiated on $\frac{24}{7}$ FLiLitechnology.